A.G. Endegnanew, J. Beerten and K. Uhlen, “Dynamic interactions between asynchronous grids interconnected through an MTDC system,” *Proc. CIGRE International Symposium HVDC Systems and Markets Integration 2015,* Lund, Sweden, May 27-28, 2015, 7 pages.

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LUND 2015

Dynamic interactions between asynchronous grids interconnected through an MTDC system

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SUMMARY

The large-scale integration of renewable energy sources in the power system, combined with the need for an increased transmission capacity has led to a growing interest in multi-terminal high voltage dc (MTDC) grids. In the future, these grids will be integrated with different existing asynchronous ac grids, eventually resulting in hybrid AC/DC power systems. This paper investigates interactions between asynchronous ac grids in a hybrid AC/DC power system. In the study, a symmetrical monopolar ±400kV four-terminal VSC-based MTDC grid connected to three different multi-machine ac systems is modelled in DIgSILENT *PowerFactory*. One of the ac grids has four generators while the others have two generators each. Governor and automatic voltage controllers are included for each generator so as to capture the complete generator dynamics. DC cables are modelled as PI models with lumped parameters. All dc grid terminal converters are operating in dc droop and reactive power control modes. A small signal analysis is carried out in the test system to investigate interactions between asynchronous ac grids. From the modal analysis of the poorly damped eigenvalues, it is shown that speed state variables of all generators in the study system are observable in these modes; indicating dynamic interactions between generators located in asynchronous ac grids. The change in the level of these dynamic interactions is studied for different time responses of the MTDC terminal converter controllers. It is found that faster and slower converter control response times lead to lower and higher interactions between the asynchronous ac grids, respectively. Results from a time domain simulation of the study system for a fault in one of the ac grids support the findings of the small signal analysis. The study results show that dynamic coupling exists between ac grids across dc grids and that the level of interaction is influenced by the converter controller settings.

KEYWORDS

Small signal stability – VSC MTDC – AC interactions – Hybrid AC/DC systems

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1. INTRODUCTION

The large-scale integration of renewable energy sources in the power system, combined with the need for an increased transmission capacity has led to a growing interest in multi-terminal high voltage dc (MTDC) grids. In terms of dc grid control, dc voltage droop control is considered as the preferred method to ensure the power balance after contingencies in HVDC systems [1, 2]. An important research topic is the dynamic interactions between MTDC grids and the ac systems. In recent years, different methods for building small signal model of dc grids [3] in combination with ac grids [4-6] have been presented in literature. In [6], the interaction between ac and dc grids is investigated by using modal analysis. Recently, reference [7] analysed the small signal stability of the CIGRE test grid system and studied the effect of using different controller types. However, previous small signal stability studies have largely focused on the modelling of the different MTDC system components and limited themselves to parametric sensitivity studies to reveal instabilities in the respective subsystems. Although in essence, the dc voltage droop control is a distributed system control, which might cause an increased coupling of dynamic phenomena in different subsystems, little work has been conducted so far to study possible coupling of ac system dynamics through MTDC systems. This paper aims at addressing this lacuna by focusing on identifying interactions between the different ac systems connected to the same dc grid. Electro-mechanical modes, in particular, are associated with synchronous generators, their natural frequencies of oscillation, and how the generators interact with each other. The method for studying this phenomenon in synchronously interconnected power grids is well established. This paper deals with a case where synchronous generators are located in different ac grids, which are linked through a dc grid. The study investigates interactions between the electro-mechanical modes of synchronous generators across the dc system and how the MTDC converter controller tuning influences these interactions. Modal analysis is used in order to identify these interactions and the findings are verified through time domain analysis.

2. SYSTEM MODELLING

Figure 1 shows the test system used to investigate interactions between asynchronous ac grids connected through an MTDC grid. It is a symmetrical monopolar ±400kV four-terminal VSC-based MTDC grid connected to three different multi-machine ac systems, modelled in DIgSILENT *PowerFactory*. In total, there are eight synchronous generators in the test system. AC grid #1 has four generators and is largely based on the two area system in presented [8]. Identical grids with two generators are used for AC grid #2 and #3. Governor and automatic voltage controller models are included for each generator so as to capture the complete generator dynamics.

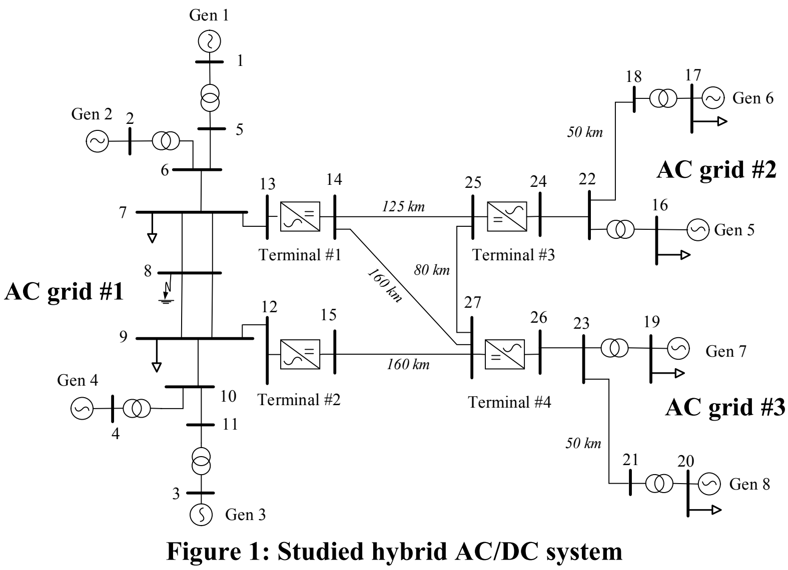

Figure 1: Studied hybrid AC/DC system

The dc grid has a symmetrical monopole configuration. DC cables are modelled as PI models with lumped parameters. Two of the dc grid terminals (#1 and #2) are connected to the same ac grid with two long transmission lines between them on the ac side. The other two dc grid terminals (#3 and #4) are connected to different ac grids each. Converters at terminals #1 and #2 operate in rectifier mode while converts at terminals #3 and #4 operate in inverter mode. The initial steady state dc grid voltages and power flows at the converter terminals are presented in Table 1. A power flow out of the dc grid and into the ac system is defined as positive.

Table I : Initial power flow and dc voltage values at MTDC converter terminals

Terminal #	**1**	**2**	**3**	**4**
P_{rated} **(MW)**	750	1000	900	800
U_{rated} **(kV)**	400	400	400	400
$P_{initial}$ **(MW)**	-500	-800	600	685.4
$U_{initial}$ **(kV)**	406	401.1	399	400

All dc grid terminal converters are operating in dc droop and reactive power control modes. DC droop control is a distributed type of converter control where more than one converter participate in the dc voltage control by contributing balancing power. It is considered as the most appropriate control strategy in MTDC grids because it provides higher reliability as the system is not dependent on a single converter to control the voltage. Furthermore, the strategy does not require communication. The steady state equation of a dc droop controller is:

$$P^* - P + k_{droop}\left(U_{dc}^* - U_{dc}\right) = 0 \quad (1)$$

Where P^* and U_{dc}^*, and P and U_{dc} represent reference and measured active power and dc voltage, respectively. The droop constant k_{droop} defines the relationship between the change in active power flow and the change in dc voltage. The block diagram of the outer converter control loops are shown in Figure 2. The internal current controllers defined in *PowerFactory* are used for the inner converter control loops.

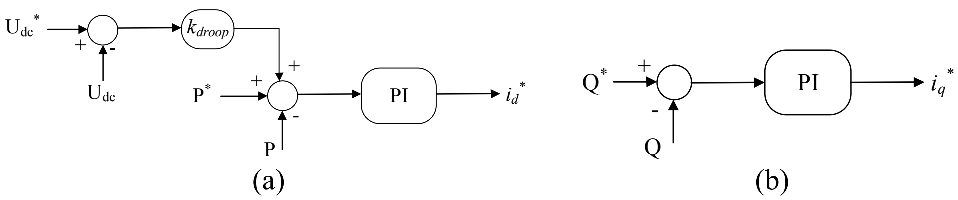

Figure 2: Converter outer converter control loop: (a) dc voltage droop and (b) reactive power control

3. MODAL ANALYSIS

Small signal stability is defined as the ability of the power system to maintain synchronism when subjected to small disturbances [8]. Small signal stability problems are usually analysed by linearized models, and thus powerful methods based on linear algebra are used to characterize the dynamic behaviour of the system. In this case, modal analysis is used to identify electro-mechanical modes and their interactions. The dynamic behaviour of a power system can be described by a linear differential equation of the form:

$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u} \quad (2)$$

where **x** is the state vector, **u** is the input vector, **A** is the state matrix and **B** is the input matrix. Eigenvalues, also known as modes, are the roots of the characteristic equation of the state matrix **A**, and can be real or appear in complex conjugate pairs ($\lambda = \sigma \pm j\omega$). If all the eigenvalues have negative real parts, the system is stable. For each eigenvalue λ_i, one can define right ($\mathbf{\Phi}_i$) and left ($\mathbf{\Psi}_i$) eigenvectors which satisfy the equations $\mathbf{A\Phi}_i = \lambda_i \mathbf{\Phi}_i$ and $\mathbf{\Psi}_i^T \mathbf{A} = \lambda_i \mathbf{\Psi}_i^T$, respectively. The elements of each of the right eigenvectors ($\mathbf{\Phi}_i$) indicate the relative activity of the state variables when the associated mode is excited. This gives information about the observability of the different modes. The magnitudes of the eigenvector elements describe the extent of the activity, while for complex

(oscillatory) modes, the relative phase angles indicate the direction of oscillation in the associated state variables. The elements of the right eigenvectors are also called *mode shapes*. Left eigenvectors measure the activity of a state variable in an eigenvalue, and thus they contain information about the controllability of the modes. Moreover, by multiplying elements of the right and left eigenvectors, i.e. $p_{ji}=\phi_{ji}\psi_{ji}$, one can obtain an indication of the participation of state variable j in mode i (defined as participation factor p_{ji}).
The small signal stability of the hybrid AC/DC test system (Figure 1), has been studied using modal analysis in *PowerFactory*. The test system has 160 eigenvalues in total, of which 74 are real and 43 are complex conjugate pairs. Most of the complex conjugate paired eigenvalues are well damped. Table II presents eigenvalues with a damping ratio less than 15%. The list is sorted based on the damping ratio.

Table II: List of eigenvalues with low damping ratio

Name	Eigenvalues	Damped Frequency	Damping Ratio	Damping Time Const.
$\lambda_{112,113}$	-0.05 ± j3.44	0.55	0.015	19.181
$\lambda_{94,95}$	-0.2 ± j5.64	0.9	0.035	5.104
$\lambda_{92,93}$	-0.5 ± j5.86	0.93	0.085	2.003
$\lambda_{90,91}$	-0.64 ± j6.29	1	0.101	1.565
$\lambda_{88,89}$	-0.65 ± j6.35	1.01	0.102	1.536
$\lambda_{2,3}$	-154.53 ± j1428.74	227.39	0.108	0.006
$\lambda_{4,5}$	-153.28 ± j1340.65	213.37	0.114	0.007
$\lambda_{37,38}$	-3.92 ± j28.68	4.56	0.135	0.255
$\lambda_{6,7}$	-154.78 ± j1074.67	171.04	0.143	0.006
$\lambda_{8,9}$	-152.44 ± j1033.86	164.54	0.146	0.007

The least damped eigenvalues in the system are $\lambda_{112,113}$, $\lambda_{94,95}$ and $\lambda_{92,93}$ with a damping ratio of 1.5%, 3.5% and 8.5%, respectively. Based on the frequency, it can be expected that $\lambda_{112,113}$ is an inter-area oscillation mode since frequencies of inter-area modes are typically in the range of 0.4 to 0.7 Hz [8]. Meanwhile, the frequencies of modes $\lambda_{94,95}$ and $\lambda_{92,93}$ indicate local plant oscillations (typically 0.7 to 2 Hz). From the participation factors of these modes, it was found that the states in the generators in AC grid #1, #2, and #3 have the highest participation in modes $\lambda_{112,113}$, $\lambda_{92,93}$ and $\lambda_{94,95}$, respectively.

4. CASE STUDIES

In this section, the poorly damped eigenvalues identified in the previous section are analysed further. Mode shapes of the eigenvalues are studied in detail to understand interactions between asynchronous ac grids. Furthermore, the control parameters of the MTDC converter controllers are varied and its effect on the degree of interaction between the different ac grids is investigated. Finally, time domain simulation of the test system for a fault in AC grid #3 is presented to support the findings of the modal analysis.

4.1. Mode shapes

The mode shapes (right eigenvectors) of λ_{112}, λ_{92} and λ_{94} have been calculated using the *modal analysis* function in *PowerFactory*. As stated earlier, mode shapes measure the relative activity of the state variables when a particular mode is excited. Thereby, it shows how observable a mode is in a state variable. To be able to make a direct and fair comparison of mode shapes we focus on generator speeds as the state variable of interest. Table III presents the normalized mode shapes of the generator speeds for eigenvalues λ_{112}, λ_{92} and λ_{94}. The normalization of the magnitudes of the mode shapes is performed by rescaling them such that the relative contribution of the largest speed mode shape magnitude is equal to 1. This means that the mode shape magnitudes of the remaining generators is presented in reference to the generator with the largest observability.

Table III: Normalized mode shapes and angles of dominant modes in all of the ac grids

State variable	AC grid #	Mode shapes					
		λ_{112} (0.55 Hz)		λ_{92} (0.93 Hz)		λ_{94} (0.90 Hz)	
		Mag.	Angle (deg)	Mag.	Angle (deg)	Mag.	Angle (deg)
Gen1: speed	1	0.8117	24.23	0.0232	-83.82	0.0158	-82.29
Gen2: speed	1	0.6016	33.46	0.0054	69.91	0.0053	1.19
Gen3: speed	1	1	-141.6	0.0252	-77.39	0.0208	-80.77
Gen4: speed	1	0.9026	-143.66	0.0055	95.96	0.0056	3.95
Gen5: speed	2	0.0130	108.98	0.5502	97.48	0.0232	72.4
Gen6: speed	2	0.0183	107.14	1	-83.22	0.0690	-70.03
Gen7: speed	3	0.0118	109.12	0.0419	-68.99	0.5016	61.45
Gen8: speed	3	0.0167	109.01	0.0480	107.97	1	-98.51

Speed state variables of Gen3, Gen6 and Gen8 have the highest observabilities in eigenvalues λ_{112}, λ_{92} and λ_{94}, respectively. For eigenvalue λ_{112}, Gen3 has the largest magnitude followed by Gen4, Gen1 and Gen2. From the relative phase angle difference of mode shapes of λ_{112}, it can be seen that speeds of Gen1 and Gen 2 are oscillating against Gen3 and Gen4. This indicates that λ_{112} is an inter-area mode in AC grid #3. However small, Gen5-8 are also observable in λ_{112}, which indicates a coupling of this dynamic interaction (dominant in AC grid #3) with generators in other ac systems connected via the MTDC grid. A similar conclusion holds for the other two modes that are studied.

4.2. Controller tuning

To investigate the effect the tuning of converter controllers has on the interaction (and the extent to which this is translated into changes of the modes shapes), the integral time constants (T_i) were changed in the PI controller of the outer loop of the VSC converters, i.e. P and Q control (see Figure 2). The results of the modal analysis in Section 4.1 were used as a reference base case. Two cases of T_i values were considered. In the first case, T_i=0.08 was used, which made the converter respond faster compared to the base scenario. In the second case, T_i=0.5 was implemented and the response of the converter controllers was slower compared to the base scenario. The mode shapes of λ_{112}, λ_{92} and λ_{94} were calculated for the two cases, and their changes compared to the base case are presented in Table IV.

Table IV: Effect of converter parameter variation on mode shapes of poorly damped modes

State variable	AC grid #	Mode shapes					
		λ_{112} (0.55 Hz)		λ_{92} (0.93 Hz)		λ_{94} (0.90 Hz)	
		Case 1 (Δ%)	Case 2 (Δ%)	Case 1 (Δ%)	Case 2 (Δ%)	Case 1 (Δ%)	Case 2 (Δ%)
Gen1: speed	1	0.25	-7.75	**-22.22**	**9.26**	**-23.91**	**13.04**
Gen2: speed	1	0.25	-8.7	**-30.77**	**23.08**	**-25**	**6.25**
Gen3: speed	1	-0.99	-1.85	**-25.42**	**15.25**	**-26.23**	**14.75**
Gen4: speed	1	-0.99	-0.78	**-38.46**	**38.46**	**-23.53**	**23.53**
Gen5: speed	2	**-33.95**	**46.51**	-5.54	9.68	**-25**	**16.18**
Gen6: speed	2	**-33.88**	**43.42**	-0.09	3.65	**-23.27**	**11.88**
Gen7: speed	3	**-33.67**	**45.41**	**-24.74**	**15.46**	-2.59	6.4
Gen8: speed	3	**-33.57**	**42.24**	**-22.32**	**8.93**	0.65	0.99

In general, the observability of the state variables decreases in Case 1 and increases in Case 2. This means that when the converter response becomes faster, the interaction between the asynchronous grids is reduced and vice versa. The change in observability of speed state variable is small for generators in the grid where the eigenvalue is dominant. The largest relative changes occur in the speeds of the generators found in remote MTDC-connected ac systems. Similarly, a slower converter controller leads to higher degree of coupling of the dynamic phenomena in the ac systems and hence increased interactions between asynchronous grids connected through MTDC systems.

4.3. Transient study

Using the non-linear dynamic model of the power system in *PowerFactory*, a time domain study was undertaken for a three phase to ground fault in AC grid #1. The fault was applied at bus 8 at t=1s and successfully cleared after 100ms. Since the associated reduction of the ac voltages at the PCC of MTDC converters' causes the internal current limits to be reached, the fault causes a reduction in the power transferred to the dc grid (Figure 3(a)) from terminals #1 and #2, which causes the dc grid voltages to drop (Figure 3(b)). Since all converters are operating in droop control mode, the power flows at terminals #3 and #4 are also reduced during the fault to cope with the power imbalance and to contribute to the dc voltage control. This effect can be seen from Figure 3(a). Consequentially, it means that the transient disturbance in AC grid #1 causes power changes in AC grid #2 and #3 because of the actions of the dc voltage droop controllers in the MTDC converters.

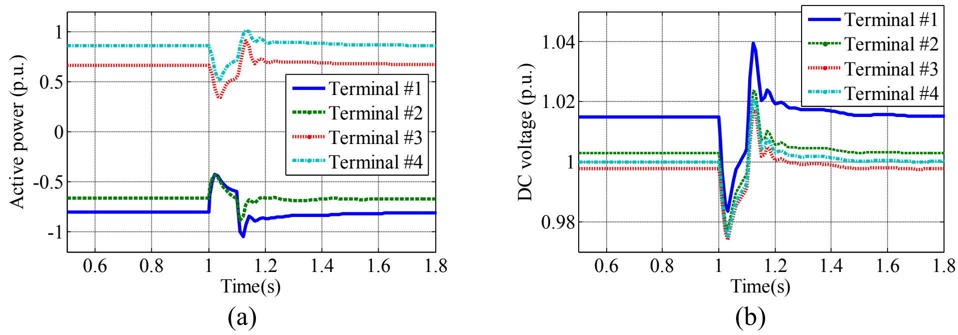

Figure 3: (a) Active power transfers and (b) DC voltages at all terminals of the MTDC grid

The abrupt change in power injections in the other ac systems causes an excitation of system modes. Figure 4 shows the generator speeds of all the generators in the studied system. After clearance of the fault, the generator speeds exhibit poorly damped oscillations. Gen 1-4 have the highest amplitude of oscillations. Gen 1&2 oscillate against Gen 3&4; which is the inter-area oscillation that was studied in the previous section (λ_{112}). Similarly, Gen 5 and 6 are oscillating against each other, which also applies to Gen 7 and 8. With the oscillation frequencies of the generator speeds equal to 0.55 Hz for Gen 1- 4, 0.89Hz for Gen 5-6 and 0.91Hz for Gen 7-8, the findings of the transient study are in accordance with the results of the modal analysis.

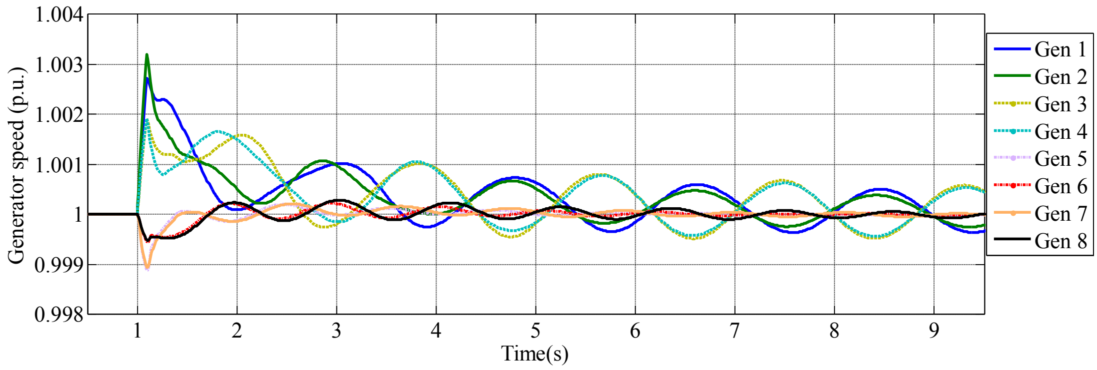

Figure 4: Generator speeds

5. CONCLUSION

In this paper, the small signal stability of a system with three multi-machine ac grids connected through an MTDC grid was analysed. The mode shapes of poorly damped eigenvalues show that speed state variables of all generators in the study system are observable in a mode; indicating dynamic interactions between generators located in asynchronous ac grids linked via MTDC. The change in the level of these interactions was studied for different time responses of the MTDC terminal converter controllers. It was found that faster and slower converter control response lead to lower and higher interactions between the asynchronous ac grids, respectively. This observation is in line with the expectations that a faster control of the power balance within the dc grid will make the connected ac systems more decoupled. However, more work is needed to fully understand the nature of the interactions, and whether there is a risk of critical resonances between the systems. Results of a time domain simulation of the study system for a fault in one of the ac grids support findings of the modal analysis. The study results show that there exists a dynamic coupling between ac grids across dc grids and that the level of interaction is influenced by the converter controller settings.

ACKNOWLEDGEMENT

The PhD study of Atsede G. Endegnanew is partly funded by Nordic Energy Research through OffshoreDC project. The research of Jef Beerten is funded by a postdoctoral fellowship of the Research Foundation – Flanders (FWO).

BIBLIOGRAPHY

[1] T. M. Haileselassie and K. Uhlen, "Precise control of power flow in multiterminal VSC-HVDCs using DC voltage droop control," in *Proc. IEEE Power and Energy Society General Meeting (PES GM)*, San Diego, USA, 2012.

[2] T. K. Vrana, J. Beerten, R. Belmans, and O. B. Fosso, "A classification of DC node voltage control methods for HVDC grids," *Electric Power Systems Research,* vol. 103, pp. 137-144, Oct. 2013 2013.

[3] P. Rault, F. Colas, X. Guillaud, and S. Nguefeu, "Method for small signal stability analysis of VSC-MTDC grids," in *Proc. IEEE Power and Energy Society General Meeting (PES GM)*, San Diego, USA, 2012.

[4] N. R. Chaudhuri, R. Majumder, B. Chaudhuri, and P. Jiuping, "Stability Analysis of VSC MTDC Grids Connected to Multimachine AC Systems," *IEEE Transactions on Power Delivery,* vol. 26, pp. 2774-2784, 2011.

[5] G. O. Kalcon, G. P. Adam, O. Anaya-Lara, S. Lo, and K. Uhlen, "Small-Signal Stability Analysis of Multi-Terminal VSC-Based DC Transmission Systems," *IEEE Transactions on Power Systems,* vol. 27, pp. 1818-1830, 2012.

[6] P. Rault, X. Guillaud, F. Colas, and S. Nguefeu, "Investigation on interactions between AC and DC grids," in *Proc. IEEE PowerTech*, Grenoble, France, 2013.

[7] M. K. Zadeh, M. Amin, J. A. Suul, M. Molinas, and O. B. Fosso, "Small-signal stability study of the Cigre DC grid test system with analysis of participation factors and parameter sensitivity of oscillatory modes," in *Proc. Power Systems Computation Conference (PSCC)*, Wroclaw, Poland, 2014.

[8] P. Kundur, *Power system stability and control*: McGraw-Hill Inc., 1994.